ARCTIC COASTAL RESEARCH ON SEA ICE AND OFFSHORE PERMAFROST

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Since 1972, the University of Alaska has been involved in sea ice and permafrost research, research specifically oriented towards the problems which will be encountered in coastal resource development in Arctic Alaska. With the discovery of huge petroleum reserves at Prudhoe Bay in 1968, petroleum geologists attempted to determine, from geophysical evidence and exploratory drilling, the location and extent of any additional petroleum reserves on the Alaskan North Slope. In 1972, it became common knowledge that oil discovery prospects were promising in the Beaufort Sea, offshore from Prudhoe Bay. Faced with the spectre of environmental problems which might be encountered in such offshore operations, the Alaska Oil and Gas Association, (AOGA), through their Arctic Research Sub-Committee, began to define those research subject areas which would be important for offshore petroleum development. At the same time, the embryonic Alaska Sea Grant Program, within the University of Alaska, recognized petroleum as a very important coastal resource which was likely to be developed in the future. Based upon common interest in coastal resource development, a dialogue was initiated in late 1972 between the Alaska Sea Grant Program, the AOGA Arctic Research Sub-Committee, and interested scientists at the Geophysical Institute of the University of Alaska.

The fundamental problem of the stresses exerted against offshore structures by the moving sea ice was quickly identified, as was the possible hazard posed by the thawing of offshore subsea permafrost beneath warm subsea oil pipelines. Consequently, a research program was quickly initiated in these two directions, funded jointly by Sea Grant and AOGA, and executed within the Geophysical Institute. The main thrust was to obtain environmental data from field measurements, and to make it available in the public domain,

to help in the development of design criteria for offshore operations. Although petroleum development appeared most imminent, it was recognized that marine transportation in Arctic regions would benefit generally from this research, as would related activities such as marine terminals.

Some measurements of sea ice motion in zones of "shorefast" ice had already been made prior to 1973 using automatically-recording wireline devices which referenced to the sea floor.[1] An alternate approach for ice movement measurement involved an ultrasonic transponder on the sea floor, with a transmitter and several receivers on the ice sheet.[2] For regions of relatively open water, subject to invasion by ice floes and ridges, the radar observation of sea ice motion pioneered by T. Tabata[3] appeared to be an attractive method. Radar offered all-weather capability from a fixed station on the shoreline, and did not rely upon recovery of data from stations based upon the ice. On the other hand, fine details of motion, on a scale of a few feet, would not be observed on radar. Since the most severe ice forces were likely to occur during ice breakup, or during ice ridge formation early in the winter, it was decided to make use of radar, since devices based upon the ice were not likely to survive such events.

A 25 kilowatt marine radar, operating at 3cm. wavelength, with a horizontal antenna beamwidth of 0.75°, was installed by J. C. Rogers and W. M. Sackinger at the Naval Arctic Research Laboratory at Point Barrow, Alaska, in March of 1973. Radar images were obtained by direct reflection of the beam from ice ridges, and a photograph of the screen was taken every 150 seconds with a 35 mm time-lapse movie camera. The resulting photographic data, recorded nearly continuously since that time, has been scanned and cataloged. Several

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events involving extreme ice motion have been analyzed.[4,5,6] Rogers, Sackinger, and Nelson[5] have described ice floes during breakup moving at speeds up to 0.92 m/sec. Parts of major grounded pressure ridges endure throughout the breakup period; ice floes move both inside and outside of the grounded pressure ridge during breakup, and move predominantly parallel to the shoreline.[5]

Since melting usually proceeds close to the shoreline first, there is the possiblity, during breakup, of a shoreward component of ice motion as well, which can thrust melting ice floes up onto the beach, building ice ridges as high as 2 meters at the beach during flexural failure,[7] and subsequently building shear ridges at greater distances offshore. Such behavior during breakup has been observed both visually and by radar, and has been reported by L. H. Shapiro.[7]

Ice ridge building in early winter has also been observed by radar. The most severe event yet observed, however, was an uncommon situation in the middle of the 1973-74 winter, when the shorefast ice moved away from the shoreline during a severe storm. This has been described in detail by L. H. Shapiro.[6] Until 26 December 1973, the ice was landfast out to beyond the 20-meter water depth contour; grounding of ridges generally occurs only out to that water depth. After an offshore wind in the range 13-24 km/hr prevailed for 15 hours, the ice broke free and drifted away from the coast at a velocity of 0.7 km/hr. The windspeed reached 30 km/hr. at the onset of ice drift. Subsequent ice motion was parallel to the coast at 3.7 km/hr. Several days later, on 31 December 1973, the wind velocity increased to 90 km/hr (with gusts to 150 km/hr) and was parallel to the shoreline. Ice drift velocity increased to 8.3 km/hr, parallel to the coast,and impact of this drifting ice removed other ice floes which had grounded earlier. This sequence represents the most severe condition of drifting ice in the shorefast zone which has yet been analyzed.[6] Based

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upon three years of observations, it is clear that drifting ice floes can assault offshore structures in the so-called "shorefast zone" during annual breakup, and occasionally in midwinter as well. During such occasions, drifting ice ridge fragments, with a thickness equal to the water depth, are also possible, with drift speeds as high as 8.3 km/hr.

Most observers of sea ice agree that the maximum ice stress which can be transmitted to an offshore structure fixed to the sea floor is limited by the breaking strength of the ice itself. The modes of formation of ice ridges around grounded structures are therefore important, for ice failure may occur in tension, compression, or shear. Numerous laboratory tests of mechanical properties had been reported[8] prior to 1973, however, and they underscored the importance of making tests on ice of known salinity, temperature, and crystal structure. Early in the program, therefore, T. E. Osterkamp and T. O'D. Hanley became involved in studies of the ice salinity and structure. At the same time, R. D. Nelson installed uniaxial stress transducers in the sea ice, to continuously monitor and record the naturally-occurring stresses in the shorefast ice. These transducers showed[5] periodic stresses in shorefast ice which were caused by tidal fluctuations, and which did not exceed 50 psi in compression. In late spring, compressive stresses near the surface were correlated with solar heating effects.[9] This transducer design, together with its amplifier/recorder package and battery power supply, has been used extensively at Point Barrow, Prudhoe Bay, MacKenzie Bay, and Resolute Bay for a variety of ice stress measurements during both natural and artifically-induced loading experiments. Additional information has been given by Nelson.[5,9,10,11,12]

At the outset of the program, it was realized that tides, winds, temperatures, and ocean currents would affect the movement and the stresses in sea ice. Routine monitoring of tides, temperatures, and winds was initiated; early

current measurements[13] showed that currents beneath the shorefast ice were very small, so that routine current monitoring was not attempted. The pack ice internal forces, generated by winds acting over very large distances, caused ice motion at times when local conditions were relatively calm. Through the use of satellite imagery from NOAA 2 and 3, ERTS, and LANDSAT, it was possible to observe ice motion on a large scale,[14] just as has been done in the AIDJEX program. The effect of the shoreline in constraining ice motion, causing leads to open for distances of over 100 km, was clearly observed by L. H. Shapiro.[15,2] Correlation with marine mammal migration patterns was also possible.[15,24]

Satellite imagery has proven to be a powerful tool in delineating the shorefast ice throughout the seasons of the year, as had been shown by W. Stringer.[16,17,18] Ice motion on a large scale[19,20,21,23] correlated with motion observed locally at Point Barrow, as well as with winds. A method for relating pressure forecasts and ice motion forecasts was also shown after the particularly anomalous ice behavior of the summer of 1975.[22,22a] G. Wendler and K. O. L. F. Jayaweera found [22,22a] that the monthly average pressure maps, showing the deviation of the 700 mbar level from the mean, could be used to calculate deviations of geostrophic winds from the mean, which correlated with average ice movements observed by satellite techniques. This offers the possibility of long term ice motion forecasting; further examination of this technique is in progress.

A second topic of concern in 1973 was offshore subsea permafrost. As an initial step in the investigation of offshore permafrost, the Sea Grant/AOGA program contributed to the support of the drilling and coring efforts already started by R. I. Lewellen[25,26] near Pt. Barrow. Using the shorefast ice as a platform, Lewellen was able to obtain samples of material from beneath the sea

floor in the vicinity of Point Barrow, and also a temperature profile with depth. As a complimentary approach, seismic refraction was used to map permafrost beneath the barrier islands and Elson Lagoon, in the same area. J. C. Rogers et. al.[27] found ice-bonded permafrost on Point Barrow using this technique, but found that the upper boundary of the ice-bonded permafrost dipped sharply to an undetectable depth at the transition between tundra and beach. No ice-bonded permafrost was detected beneath the barrier islands or beneath Elson Lagoon using this seismic refraction technique.[27].

It was obvious in 1974 that the major area of concern for offshore permafrost was Prudhoe Bay. The completion of the Alyeska Pipeline Service Co. road from Fairbanks to Prudhoe Bay made it logistically feasible to drill and sample for offshore permafrost there. A cooperative arrangement was made with the Geotechnical Division, Alaska Department of Highways, which involved the use of their drilling equipment, expertise, and staff to obtain samples of offshore subsea material at Prudhoe Bay. This drilling program, under the direction of W. D. Harrison and T. E. Osterkamp, was logistically and scientifically successful,[28] resulting in samples and information from 17 locations along a transect extending offshore into Prudhoe Bay a distance of approximately 3.4 meters. They found[28] that the ice-bonded permafrost extended beneath the sea, with the upper boundary gradually dipping to approximately 5 meters below the sea floor in that region where sea ice annually freezes to the sea floor (up to 2 meters of water depth). Beyond that distance (approximately 500 meters from shore at the site chosen) the upper boundary dipped sharply to a level 20 meters below the sea floor, an effect which they attribute to the presence of relatively warm, circulating sea water on the sea floor throughout the year. The upper boundary of the ice-bonded permafrost continued to dip gradually to a level of approximately 50 meters at a distance of 3.4 km from shore. Temperature measurements[28] indicated that the upper boundary of the

ice-bonded permafrost was very close to -1.8^{0}C. A theoretical study of the movement of the boundary is currently underway. Because of the coarse sand and gravel material in that particular region, it appears that convective transport of brine may be a dominant mechanism, driven by density gradients.[29] Other mechanisms such as thermal conduction and salt diffusion[30,31] may be significant in fine-grained sediments found in other coastal regions, however.

To explore the geographical distribution of offshore ice-bonded permafrost, J. C. Rogers and J. A. Morack have conducted seismic refraction surveys, in cooperation with P. Barnes and E. Reimnitz of the U. S. Geological Survey. From the U.S.G.S. boat Karluk, limited data was obtained in the Chukchi and Beaufort Seas in 1975, despite the anomalous presence of sea ice during most of the summer season. Additional data from Prudhoe Bay has been obtained in 1976. A comparison of seismic data with the drilling results mentioned above is given[32,33] in Figures 6 and 7, both taken along the same line. Good agreement is obtained between the two methods. Further analysis of data taken in the Prudhoe Bay region is in progress.

In retrospect, the Arab oil embargo and the resulting energy crisis in 1973 had a remarkable effect on this research program. As a result of the circumstances of that year, a very high national priority was placed upon the exploration and development of domestic petroleum reserves. The Alaskan Outer Continental Shelf was quickly identified as a target, and tentative schedules were published for leasing of Alaskan offshore lands by the Department of the Interior. At the same time, the Department of the Interior initiated a massive program of environmental assessment of the Alaskan Outer Continental Shelf, (OCSEAP), with the National Oceanic and Atmospheric Administration (NOAA) taking the responsibility for program management. The OCSEAP program has recently been described in a previous issue[34] of the Arctic Bulletin.

The breadth of the OCSEAP program was such as to encompass all aspects of the environment, including particularly the chemical and biological oceanography, benthic fauna, marine birds and mammals. However, it was recognized early in the planning stages of the OCSEAP program that sea ice and permafrost hazards could indirectly affect the environment adversely, if offshore petroleum activities did not take these hazards into account. To better define these physical hazards, and to provide a basis upon which environmental decisions and regulations could be made, sea ice and offshore permafrost research were included in the OCSEAP program. It is a tribute to the foresight of the Alaskan Sea Grant Program, and to AOGA, that this important area of research was identified and started at an early date, and that the OCSEAP program recognized its importance. At the University of Alaska, the research described above continued on, and was expanded in scope and in detail, with the advent of OCSEAP in June 1975. In accordance with a long-established philosophy of providing support to important marine activities primarily in their embryonic stages, the Alaska Sea Grant Program has gradually turned over many of the responsibilities for sea ice and offshore permafrost research to OCSEAP and other agencies, who have a continuing long-term mission to investigate important environmental aspects of the Arctic.

Today, about 15 scientists are involved in research on sea ice and offshore permafrost at the Geophysical Institute of the University of Alaska. A great deal of information has been already obtained, and has been reported in the publications referenced. Many significant questions still need to be answered, however, and are the subject of continuing research.